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08MAR99 E430791-1 000001
P01/7700 0.00 - 9905196.3

Request for grant of a patent

(See the notes on the back of this form. You can also get an explanatory leaflet from the Patent Office to help you fill in this form)

The Patent Office

Cardiff Road
Newport
Gwent NP9 1RH

1. Your reference — 4802/CJGL

2. Patent application number *(The Patent Office will fill in this part)* — ~~05 MAR 1999~~ 9905196.3

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

   FUJITSU TELECOMMUNICATIONS EUROPE LTD.
   Solihul Parkway
   Birmingham Business Park
   Birmingham, B37 7YU, ENGLAND
   and
   Robert Joseph MEARS
   50 Hurst Park Avenue
   Cambridge, CB4 2AE, ENGLAND

   Patents ADP number *(if you know it)* — 7333417[illegible]; 7179591002

   If the applicant is a corporate body, give the country/state of its incorporation — The first applicant is incorporated in England and Wales

4. Title of the invention — APERIODIC GRATINGS

5. Name of your agent *(if you have one)* — ABEL & IMRAY

   "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

   20 Red Lion Street
   London
   WC1R 4PQ

   Patents ADP number *(if you know it)* — 174001

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number

Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

7. ~~If this application is divided or otherwise~~ derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application	Date of filing *(day / month / year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:*
   a) any applicant named in part 3 is not an inventor, or
   b) there is an inventor who is not named as an applicant, or
   c) any named applicant is a corporate body.
   See note (d))

   Yes

9. Enter the number of sheets for any of the following items you are filing with this form. Do not count copies of the same document

Continuation sheets of this form	
Description	4
Claim*(s)*	1
Abstract	
Drawing*(s)*	

10. If you are also filing any of the following, state how many against each item.

Priority documents	
Translations of priority documents	
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	
Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. I/We request the grant of a patent on the basis of this application.

Signature Abel & Imray Date

ABEL & IMRAY 5th March, 1999

12. Name and daytime telephone number of person to contact in the United Kingdom C. J. G. LEGG - 0171-405 0203

Warning

After an application for a patent has been filed, the Comptroller of the Patent Office will consider whether publication or communication of the invention should be prohibited or restricted under Section 22 of the Patents Act 1977. You will be informed if it is necessary to prohibit or restrict your invention in this way. Furthermore, if you live in the United Kingdom, Section 23 of the Patents Act 1977 stops you from applying for a patent abroad without first getting written permission from the Patent Office unless an application has been filed at least 6 weeks beforehand in the United Kingdom for a patent for the same invention and either no direction prohibiting publication or communication has been given, or any such direction has been revoked.

Notes

a) If you need help to fill in this form or you have any questions, please contact the Patent Office on 0645 500505.

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Aperiodic Gratings:

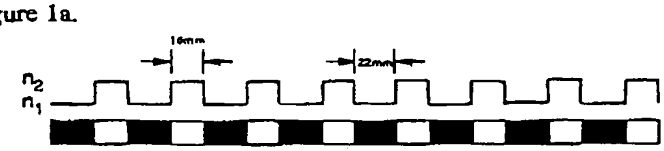
Background

There has been much interest in both regular and chirped grating structures to define/modify device optical passband characteristics. Examples include Fibre Bragg Gratings (FBGs) and apodised FBGs, where a slowly-varying chirp is superposed on the grating. Periodic (grating) structures have been the focus of much attention in a very wide range of applications, e.g. photonic crystals, for which the band structure is defined by a close analogy with the well-known (Bloch) periodic lattice analysis of solid-state physics.

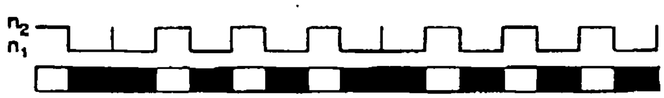
By means of a simple approximate analysis, we have found aperiodic structures which exhibit a controllable band structure, although in general, such aperiodic structures do not exhibit a useful band structure. At the heart of this analysis is the understanding that is not the regular periodicity of the real lattice, but rather the existence of well-defined spatial frequencies, (e.g. as revealed by the Fourier Transform (FT) of such an aperiodic structure) which distinguishes a 'useful' aperiodic structure from the vast majority of non-useful (random) aperiodic structures.

Embodiment

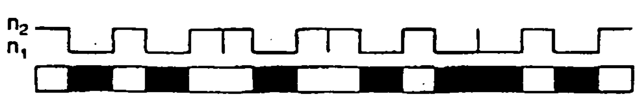
We have performed an experiment at microwave frequencies, rather than optical frequencies, making it easier to demonstrate the proof-of-principle. A microwave source was used, tuneable from 2-4GHz, hence with wavelengths varying from 150mm to 75mm respectively in free space. The length of the binary APBG was close to 320mm, and perspex (refractive index n_2=1.37) was used to cause the perturbation in refractive index, and hence backward coupling. Basic units, consisting of a 22mm length of air (refractive index, n_1=1), and an associated 16mm (~22mm/n_2) length of perspex, were used to construct the APBGs. Each basic unit was of the equivalent optical path length. Taken together, the smallest spatial period in an APBG could thus be a base cell of length 38mm, consisting of a unit length of air and a unit length of perspex. This base cell could then be repeated 8 times within the 320mm length of the transmission line, as shown in figure 1a.



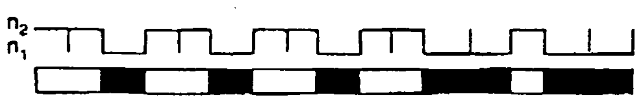
(a) 3.41GHz



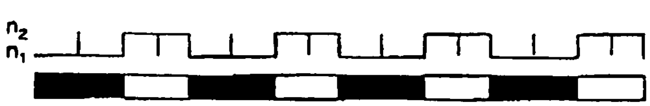
(b) 2.98GHz



~~(c) 2.55GHz~~



(d) 2.13GHz



(e) 1.70GHz

Figure 1: Structures of APBGs for various bandgap frequencies

A spatial period Λ will reflect wavelengths given by $\Lambda = (2m-1)\frac{\lambda}{2}$, where m is the grating order, given by m=1 in this case. However since the grating is made of materials with very different refractive indices, this formula is too simple. Instead, it is better to consider the spatial period Λ' as if both materials had the same refractive index, (i.e. n_1=n_2) but that there was still the same reflection at their interface. In this case, (assuming n_1=n_2=1), $\Lambda' = 2\times 22\text{mm} = 44\text{mm}$. The wavelength of maximum reflection (and hence minimum transmission) would thus be $\lambda = 2\Lambda' = 88\text{mm}$, corresponding to a bandgap frequency of f=c/λ=3.41GHz.

The next available regular grating, using the same sized base cells would have a spatial period of $\Lambda' = 88\text{mm}$ (as shown in figure 1e), and would tend to have an associated bandgap frequency of 1.70GHz,. Generally it wouldn't be possible to tune to intermediate frequencies between 1.70 – 3.41GHz using the same dimensioned base cells. However, an aperiodic grating does allow this to happen, and the APBGs for these intermediate frequencies are shown in figures 1b – 1d.

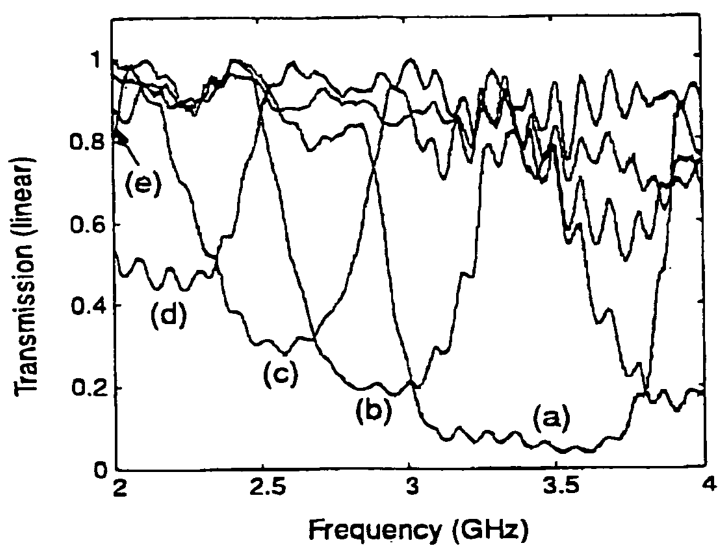
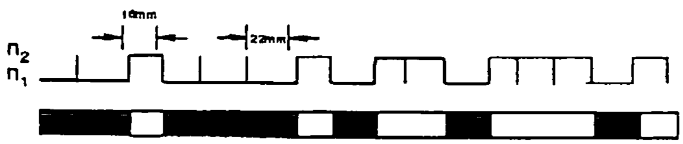


Figure 2: Single Bandgap Spectra for APBGs of figs. 1a – 1e

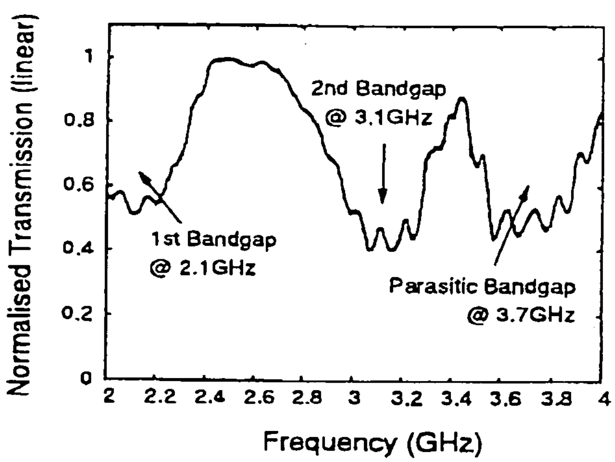
Figures 2a-2e depict the measured transmission spectra of the APBG structures depicted in figures 1a-1e. Figures 2a and 2e show the transmission spectra for the regular gratings of period 38mm and 76mm respectively. The bandgap of figure 2a is very well defined, with a centre frequency of about 3.4GHz. However, the bandgap centre frequency of figure 2e is less than 2GHz (i.e. ~1.7GHz), and we can only see ~~the falling edge of the bandgap at about 2.0GHz. Figures 2b-2d show the bandgap being shifted in~~ incremental steps of about 0.43GHz, between 1.7GHz and 3.4GHz, by using aperiodic Bragg gratings. Figure 2b has a bandgap centre frequency of 3.0GHz, while figure 2c is at 2.6GHz, and figure 2d is at about 2.2GHz, agreeing well with the theoretical bandgap frequencies. The strength of the bandgap for aperiodic Bragg gratings is not as large as for a regular Bragg grating, so that the transmission at the bandgap centre frequency tends to be higher. A longer APBG with more segments would ensure a stronger bandgap.

Multiple Bandgaps

An aperiodic Bragg grating can also be designed to exhibit multiple bandgaps. Such an APBG is shown in figure 3a, and has been designed to exhibit bandgaps at 2.13GHz and 2.98GHz. The APBG is designed to provide the same functionality, as afforded individually by the APBGs shown in figures 1b and 1d. The resulting transmission spectrum is depicted in figure 3b, and shows that the corresponding bandgap centre frequencies lie at about 2.1GHz and 3.1GHz, which while not exactly matching the designed bandgap frequencies, still shows close correspondence. Because the APBG is having to do more 'work', in the sense that it is trying to produce 2 bandgaps, rather than just one, the resulting bandgaps tend to be weaker than those shown in figures 2b and 2d. There also appears to be an additional 'parasitic' bandgap at 3.7GHz, which seems to be closely related to the bandgap at 3.0GHz, as it is also evident in figure 2b. This is probably due to an additional parasitic resonance between spatial components of the APBG designed to resonate at 3.0GHz and the experimental waveguide apparatus.



(a) Structure of APBG with Multiple Bandgaps at 2.13GHz and 2.98GHz



(b) Transmission Spectrum of Multiple Bandgap APBG

Figure 3: Multiple Bandgap APBGs

A. Definition of an Aperiodic Structure

A.1) An aperiodic grating/hologram is a structure which is not periodic, or does not repeat itself.

A.2) An aperiodic grating/hologram is a structure which cannot be expressed as a simple transformation of a regular grating. Often, a chirped grating is described as an aperiodic grating, which is technically correct, since it doesn't repeat itself. A regular grating can be mathematically described in the following manner:

$$\underline{G} = T_G(\underline{x})$$

where $\underline{G}$ = Regular Grating,
T_G = Grating Transformation/Matrix function to produce a regular grating in the spatial domain,
$\underline{x}$ = spatial dimension.

However, a chirped grating can be described by a linearly-chirped or stretched regular grating thus:

$$\underline{C} = T_G(\underline{x}^2)$$

where $\underline{C}$ = resulting chirped grating.

The spatial dimension $\underline{x}$ has undergone a simple, continuous transformation (*i.e.* it has been squared.) But a hologram $\underline{H}$ cannot be so simply expressed as the grating transformation function T_G operating on some 'simple', continuous function of the spatial dimension $f(\underline{x})$. [*n.b.* for the binary case, such a function $f(\underline{x})$ can be found – in general being an n^{th} order polynomial $f(\underline{x})$, where n – no. of elements in the hologram $\underline{H}$. However, this is not a simple function, in comparison to the chirped case, where it is merely a 2^{nd} order polynomial.]:

$$\underline{H} \neq T_G(f(\underline{x}))$$

Instead, a hologram $\underline{H}$ requires a special Hologram Transformation/Matrix function T_H to produce the aperiodic structure in the spatial domain $\underline{x}$, such that in general we have:

$$\underline{H} = T_H(\underline{x})$$

A.3) Likewise, an aperiodic grating is a structure which cannot be expressed as a finite (or limited) summation of regular gratings of varying spatial frequency (*i.e.* similar in concept to a Fourier series):

$$\underline{H} \neq \sum_i^N a_i \underline{G}_i$$

where a_i = amplitude
$\underline{G}_i$ = regular grating of i^{th} spatial frequency

A.4) Likewise, an aperiodic grating is a structure which cannot be simply expressed as a set of concatenated regular gratings of varying spatial frequency:

$$\underline{H} \neq [\underline{G}_1, \underline{G}_2, \underline{G}_3, \cdots, \underline{G}_i, \cdots, \underline{G}_N]$$

where $\underline{G}_i$ = of i^{th} regular grating, where a regular grating is defined to contain at least 1 or more periods of a regular grating unit cell (of equal mark-space ratio), e.g. for a binary regular grating, the unit cell is graphically:

B. Claims of Form of APBG

B.1) We claim an aperiodic grating structure as defined in (A).

B.2) We claim a quasi-periodic grating consisting of a set of concatenated, repeated base cells, where there are in fact subtle differences between the 'base cells', so that the overall performance is better than if

a single base cell was perfectly repeated. *i.e.* an optimisation technique such as simulated annealing, or error-diffusion has been employed to improve the overall performance of the aperiodic grating.

B.3) We claim a periodic grating consisting of a set of concatenated, repeated base cells, where the base cell is itself an aperiodic structure of the type defined in (A).

B.4) We claim an aperiodic grating consisting of a set of concatenated aperiodic structures, as defined in (A), where:

1) the aperiodic structures are all different to each other,
2) some structures are repeated 1 or more times
3) the same base structure is used throughout, as in (B.3).

C. Claims of Application of APBGs

C.1 We claim an APBG structure, designed to function as a photonic bandgap structure.
C.1.1 We claim an APBG structure defined by changes in material permittivity (both real and/or imaginary) and/or permeability (both real and/or imaginary)
C.1.1.1 We claim an APBG structure defined by spatial positions of scatterers (which may not be classical), where the APBG structure can be vertices a lattice and/or a superlattice.

(Single, multi-wavelength WDM filter)
C.1.2 where the APBG structure is along the length of a waveguide,
Where the APBG structure may appear within and/or outside the waveguiding region
Where the waveguide may be not exclusively: an optical fibre, a microwave strip line, a silica on silicon planar lightwave circuit (PLC), or a silicon on silica PLC, semiconductor laser/amplifier waveguide,

(Laser)
C.1.3 We claim an APBG structure placed within the cavity of a laser,
Where the laser may be single/multi-wavelength
Where the laser may be CW, pulsed, mode-locked
C.1.3.1 We claim an APBG structure designed as the dielectric stack in a VCSEL

(Non-Linear Effects)
C.1.4 We claim an APBG structure fabricated in and/or on a non-linear medium, designed to enhance the non-linear effect and/or effect phase-matching,
For applications such as wavelength conversion, parametric amplification (PA), 2^{nd} & 3^{rd} order nonlinear effects ($2^{nd}/3^{rd}$ harmonic generation, Kerr effect) parametric oscillators (PO), where the frequency range of application can range across the EM spectrum.

C.1.5 We claim an APBG structure designed to function as a dispersion-compensating element.

C.2 We claim an APBG structure, designed to modify an electronic bandgap structure.
C.2.1 We claim an APBG structure designed to function as an electronic superlattice structure

C.3 We claim an APBG structure designed to function as a superconducting superlattice

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Abel + Imray
F23 filed 3/4/00.